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CONDENSED SUMMARY REPORT

Study for an On-Board Electrical Power System for a Manned Orbital Space Station

Contract No. NAS 9-1307

LOCKHEED CALIFORNIA COMPANY
BURBANK, CALIFORNIA, U.S.A.

SUMMARY

I. INTRODUCTION

This report contains the results of a six-month study performed by the Spacecraft Organization of the Lockheed-California Company, in which 10- to 40-kw electrical power systems for a large manned orbital space station were compared and evaluated. The study was conducted for the NASA Manned Spacecraft Center, Houston, Texas, under Contract No. NAS 9-1307, which required the expenditure of 8,000 man-hours of work during the period of performance 6 May 1963 to 6 November 1963.

Electrical power systems, including power generation, energy storage, voltage regulation, and distribution, are considered for use in two space station configurations - the three-spoke rotating station and cylindrical zero-g station.

II. STUDY OBJECTIVE AND SCOPE

The purpose of the study was to assess the development status of solar and nuclear space power systems in the 10- to 40-kw range and to distinguish the concept most likely to meet the requirements of a large manned orbital space station with a 1- to 5-year mission.

During the initial phase of the study, the Lockheed Spacecraft Organization and NASA agreed upon the parameters of the space station configurations, the mission upon which the investigation and analysis were to be based, and the following study objectives:

1. Determine which will be the earliest available suitable system or systems.
2. Identify the problems which require solution before the systems(s) can become operational.
3. Outline programs aimed at the solution of these problems.

4. Estimate when advanced systems may be available and the advantages offered by those advanced systems.

As shown below, the complete spectra of energy sources, energy conversion, and energy storage have been considered.

Table 1

ENERGY SOURCES

• Primary Power	Nuclear Reactor Radioisotope Solar
• Emergency Power	Chemical

ENERGY CONVERSION

- Dynamic
- Photovoltaic
- Thermoelectric
- Thermionic
- Electrochemical

ENERGY STORAGE

- Electrochemical
- Thermal
- Kinetic

The space station integration aspects of the more promising candidate systems were analyzed during the evaluation and comparison phase of the study.

III. RELATIONSHIP TO OTHER NASA EFFORTS

The study is directly related to two categories of important NASA development programs: space power systems and space stations. NASA is sponsoring the development of several complete space power systems such as the solar dynamic Sunflower system, the nuclear dynamic SNAP 8 system, and the Gemini and Apollo fuel cell systems. A large number of other NASA programs are also aimed at the development of new and improved space power system components such as sealed-cell batteries, solar cells, Brayton cycle heat engines, solar concentrators, and many others.

The NASA space station programs are potential users of these systems and components. This study has been directed solely at the problem of applying these systems and components to two NASA space station configurations. However, much of the information is applicable to other configurations, to smaller space stations, and to the logistic spacecraft. The data and the results of the study can be instrumental in crystalizing the planning of both the space power system programs and the spacecraft power system configurations.

IV. METHOD OF APPROACH AND PRINCIPAL ASSUMPTIONS

Method of Approach

The study consisted of two major parallel tasks: (1) Definition of the requirements and configurations of the power systems to be evaluated and compared, and (2) assessment of the state-of-the-art of important space power system concepts and components.

Requirements of solar photovoltaic, solar dynamic, nuclear dynamic, solar thermionic, and nuclear thermionic power systems for the space station and its mission were defined in Preliminary Data Requirement forms. These PDR's were submitted to potential vendors of these systems with requests for preliminary system design data. The following companies responded with comprehensive design data for one or more systems:

Aerojet General Corporation, Azusa, California
AiResearch Corporation of Arizona
AiResearch Corporation of Los Angeles
Allison Division of General Motors Corporation
Engineered Magnetics Division of Gulton Industries, Inc.
Hamilton Standard Division of United Aircraft Corporation
Minneapolis Honeywell, Ordnance Division
Tapco Division of Thompson Ramo Wooldridge, Inc.
Westinghouse Electric Corporation

A state-of-the-art assessment was conducted to establish a basis for the selection and evaluation of candidate systems.

A comprehensive study was made of solar cells and arrays, rechargeable batteries, solar concentrators, heat engines, radioisotope heat sources, fuel cells, and electromagnetic generators. Cursory investigations were made of thermionic and thermoelectric conversion, concentrator orientation mechanisms, thermal and kinetic energy storage, and nuclear reactors for space vehicles.

Data for the state-of-the-art studies were obtained from the published literature, from space programs in the planning and operational phases, and from the following companies who cooperated by responding to specific requests for information:

Allis Chalmers Corporation
Alkaline Battery Division of Gulton Industries
Eagle Picher Corporation
Electro-Optical Systems, Inc.
The General Electric Company
Hoffman Electronics Corporation
Ryan Aeronautical Corporation
Sonotone Corporation
Yardney Electric Corporation

The data obtained in response to the PDR's and from the state-of-the-art assessment were used to configure the systems which were compared and evaluated.

The following principal assumptions were made:

Mission duration: 1 to 5 years

Crew complement: 18 to 24 men

Orbit altitude: 253 to 272 nautical miles

Orbit inclination: 28.5 degrees

Space Station Configuration

Three-spoke radial rotating

Cylindrical zero-g

Launch Vehicle: Saturn 5

Launch date: Not specified; time is a parameter

Electrical power requirement: 18-, 27-, and 40-kw average; profiles to be supplied by NASA

Reliability

Mission:	0.90
Prime Power Source:	0.95
Crew Survival:	0.99

V. BASIC DATA GENERATED AND SIGNIFICANT RESULTS

The state-of-the-art assessment resulted in the selection of the following power systems for study in depth:

- Solar photovoltaic system using n/p silicon solar cells and silver-cadmium (Ag-Cd) batteries for energy storage.
- Solar dynamic systems using thermal energy storage and Rankine, Stirling, and Brayton cycle engines.
- Nuclear-reactor dynamic systems using Rankine and Brayton cycle engines.
- Radioisotope dynamic system using a Brayton cycle engine.

SOLAR PHOTOVOLTAIC POWER SYSTEM

Conceptual designs of 18-, 27-, and 40-kw solar photovoltaic power systems have been prepared. Electrical power modules of 3- and 6.75-kw capacity are used. The 18-kw system is composed of six 3-kw modules and the 27- and 40-kw systems are composed of multiples of 6.75-kw modules. Table 2 below is a summary of the important solar photovoltaic system data generated.

Table 2

SOLAR PHOTOVOLTAIC SYSTEM DESIGN SUMMARY

Item	18-kw system	27-kw system	40-kw system
No. of power modules	6	4	6
Power per module	3 kw	6.75 kw	6.67 kw
Solar cell	n/p silicon	Same	Same
Battery type	Silver-cad	Same	Same
Solar cell array area (sq ft)	4380	6592	9768
Array wt *(lb/ft^2)	1.27	1.27	1.368
*Total battery wt (lb)	2670	3880	5820
Power conditioning and control equipment wt (lb)	589	612	933
*System wt (lb)	8821	12,842	20,153
System specific wt (lb/kw)	491	477	504

*There are slight weight differences between the rotating station and zero-g station system weights. These are average figures.

A power distribution and load bus transfer system concept was developed to show the mode of operation during launch and ascent, predeployment, normal and abnormal in-orbit conditions, and emergency conditions. A detail design was made of the 40-kw solar cell array for both space stations. Structural, vibrational, thermal, and weight analyses were performed on these array designs.

SOLAR DYNAMIC POWER SYSTEMS

Conceptual designs of the solar dynamic systems studied were developed by Thompson-Ramo Wooldridge (TRW), Allison, AiResearch, and Sundstrand. Table 3 is a summary of the important parameters and data of the typical 13.5- to 15-kw solar dynamic power modules proposed. Three of these approximate a 27-kw system in which any two can supply the average power.

Table 3

COMPARISON OF SOLAR DYNAMIC SYSTEM CONCEPTS

	Tapco	AiResearch	Allison	Sundstrand
System kw	14.2	15	14.5	13.5
Heat engine	Rankine	Brayton	Stirling	Rankine
Working fluid	Mercury	Argon	Helium	Biphenyl
Energy storage medium	Lithium Hydride	Lithium Flouride	Lithium Hydride	Lithium Hydride
Collector type	Petal Unfurable	Inflatable Rigidized	Fresnel	Inflatable Rigidized
Collector area (sq ft)	1910	1450	1410	1320
Collector wt (lb)	439	235	705	285
Engine RPM	40,000	64,000	2,400	24,000
Max. cycle temp.	1250°F	1500°F	1212°F	700°F
Radiator area (sq ft)	84.5	596	515	260
Total wt (lb)	1561	1574	2083	1387

The system proposed by Tapco was selected as a typical solar dynamic power system to be used in the comparison with other types of space power systems for the space station. This selection was made because these data were relatively more complete than the others, because they were specifically oriented to the requirements of the study, and because Tapco's Sunflower development and test program are the source of the most extensive space power dynamic system test data available at the time. Table 4 is a summary of the important 18-, 27-, and 40-kw solar dynamic system data based on the Tapco 10-, 14.2-, and 21.8-kw modules. Three modules constitute systems in which any two can supply the total peak power requirement of the assumed load profile.

Table 4

SOLAR DYNAMIC SYSTEM DESIGN SUMMARY

	18 KW System	27 KW System	40 KW System
KW/Module	10.0	14.2	21.8
Modules Required	3	3	3
Wt/Module (lb)	1211	1561	2125
System wt (lb)	3439	4231	6081
Specific wt (lb/kw)	174	149	140
Concentrator area per module (sq ft)	1494	1910	2760
Condenser subcooler area per module (sq ft)	69.3	84.5	120
System exposed area (sq ft)	4690	5983	8640
Average solar power input per orbit (kw)	317	405	588
Overall system efficiency	6.3%	7.0%	7.45%

NUCLEAR POWER SYSTEMS

Three nuclear power systems were considered. The reactor-Rankine cycle system proposed by Aerojet-General is a SNAP-8 system modified for a manned spacecraft application by incorporation of a redundant turboalternator to raise the reliability level. The reactor and radioisotope Brayton cycle systems proposed by AiResearch each consists of three independent turboalternator units and their respective heat sources — a SNAP 8 reactor or a bank of strontium 90 radioisotope capsules. A study was made of the possible methods of incorporating these into the space stations and their effect on shield weight and station operation. Table 5 shows the total weight of the nuclear power systems. It is readily seen that total weight decreases very little with decreasing power system size.

Table 5

TOTAL WEIGHTS OF NUCLEAR POWER SYSTEMS (pounds)

	Reactor-Rankine	Reactor-Brayton	Isotope-Brayton
Spin Axis Mounting	(1)	(1)	(2)
18 kw	38,938	37,340	5100
27 kw	40,050	38,855	6285
40 kw	41,468	40,660	7745
Spin Plane Mounting			(3)
18 kw	19,373	17,160	4880
27 kw	19,925	17,905	5940
40 kw	20,863	19,080	7360
Zero g			(3)
18 kw	16,803	14,590	4290
27 kw	17,375	15,355	5320
40 kw	18,193	16,410	6670

(1) Separation distance from source to nearest part of station = 50 ft

(2) Separation distance = 122 ft

(3) Separation distance = 40 ft

System Comparison and Evaluation

The candidate solar and nuclear power systems were compared and evaluated, using as criteria weight, cost, availability, reliability, logistic requirements, and influence on station design and operation. Some of the results are summarized in the following bar charts. In the reliability analysis, the candidate system configurations were equalized to the given minimum 0.95 level of

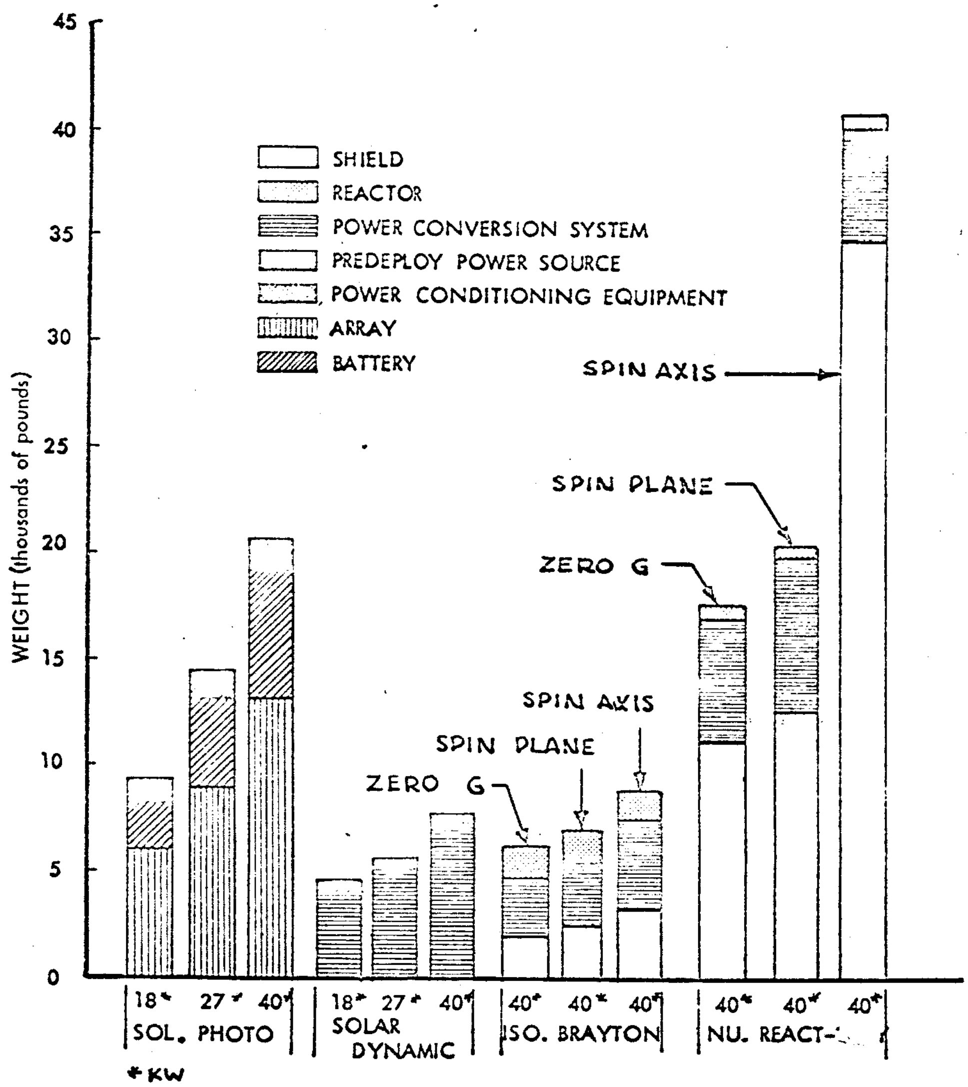

FIG. 1 COMPARATIVE WEIGHT OF SPACE STATION POWER SYSTEMS

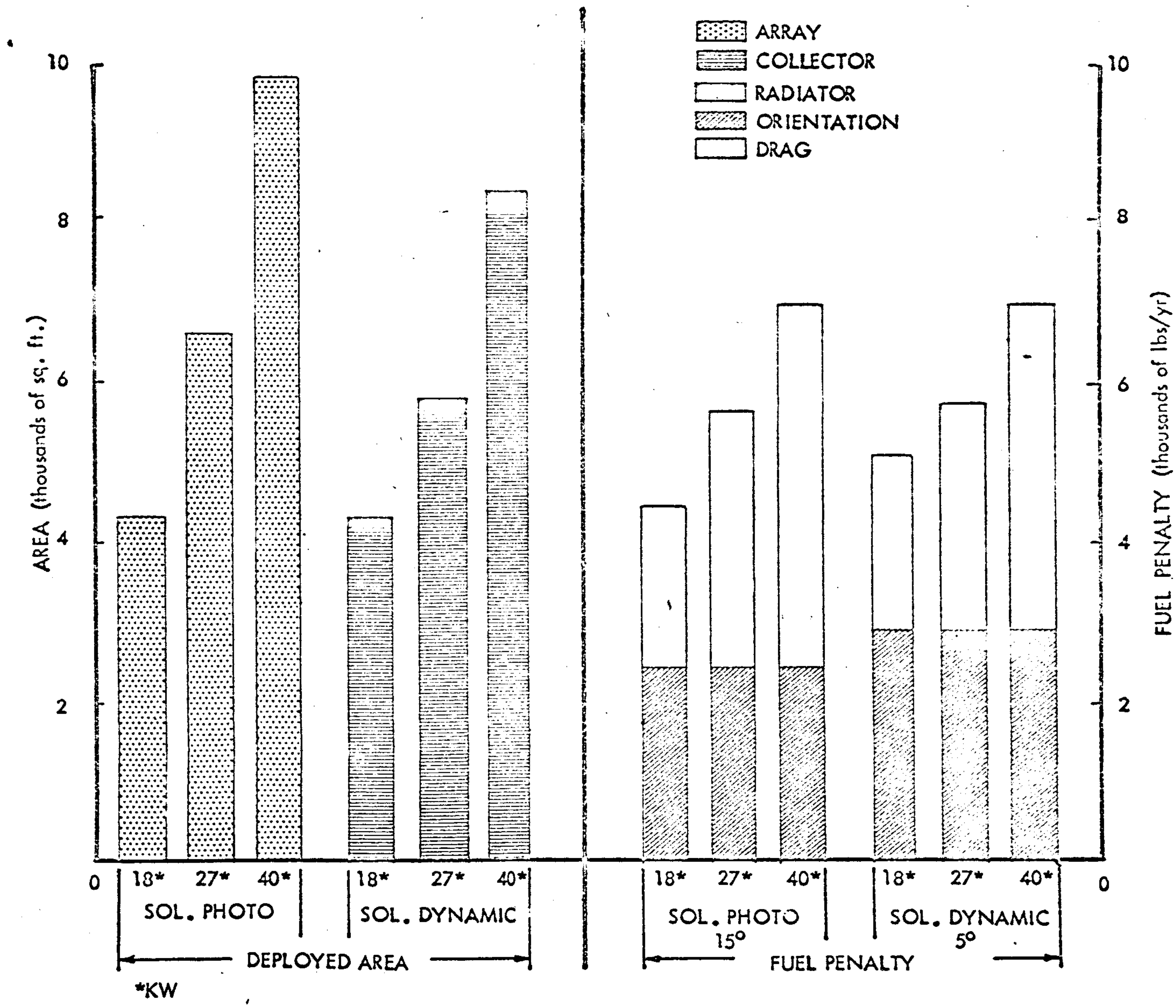

FIG. 2 COLLECTOR/ARRAY/RADIATOR AREA AND FUEL PENALTY DUE TO ORIENTATION AND DRAG

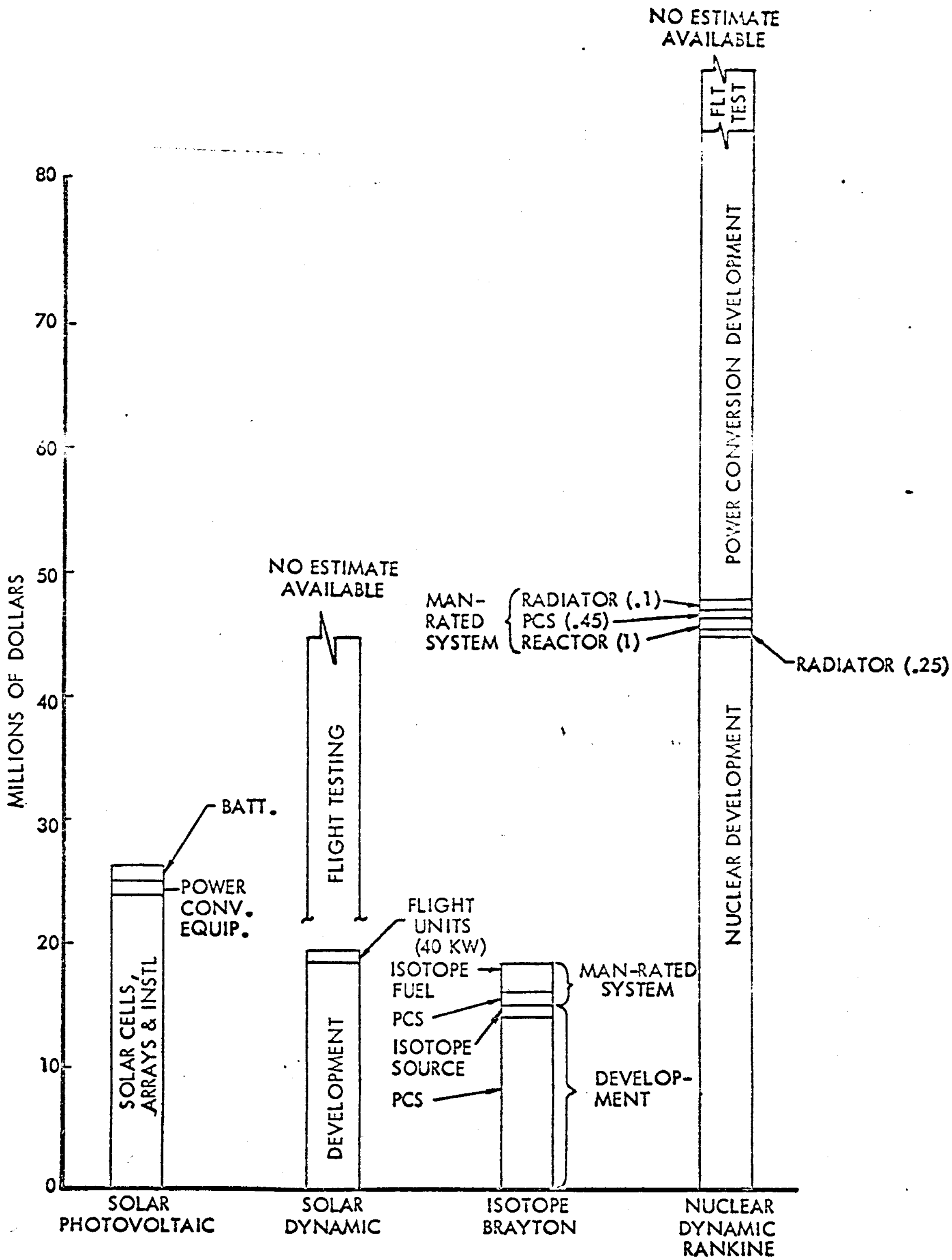

FIG. 3 ESTIMATED COST OF SPACE STATION POWER SYSTEMS

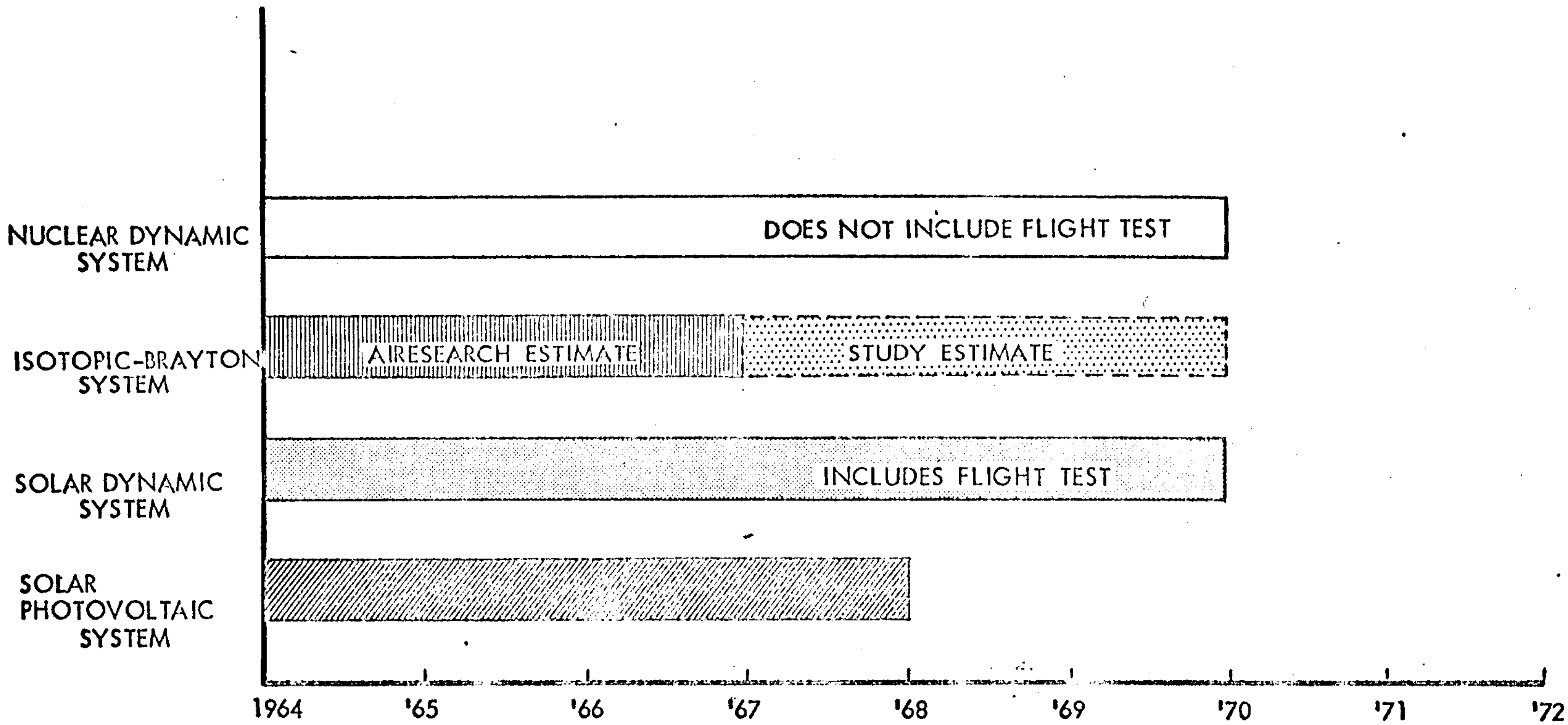

FIG. 4 ESTIMATED DEVELOPMENT SCHEDULE

reliability by incorporation of redundant components. To bring the solar and nuclear dynamic systems up to this level, it is necessary in most instances to incorporate redundant rotating units into each power module, and redundant reactors into the nuclear reactor systems.

This analysis was based on failure rate data supplied by the potential vendors. Details of the method of integrating the redundant components and the effect upon overall reliability of the additional mechanisms required to transfer them in and out of the system have not been assessed. The realiability goals can be achieved with the solar photovoltaic power system with considerably higher confidence than with any dynamic system. It is the only system that can supply the emergency power required for crew survival without the use of an additional emergency power source.

The realiability analysis was based on the assumption that basic system problems will be resolved during the normal course of development. Large sealed cell batteries must be developed for the solar photovoltaic system. Silver-cadmium batteries are preferred because of higher specific energy and charging efficiency. The 40- to 60- foot diameter solar concentrators required by the solar dynamic systems are beyond the current state-of-the-art. There is no evidence that the necessary level of reliability of the rotating components of the dynamic systems can be demonstrated within the projected development time span. It was concluded that the system most likely to be available at an early date and able to meet the space station requirements is the solar photovoltaic power system using batteries for energy storage.

Thermionic and thermoelectric conversion were also considered. Thermoelectric conversion cannot be considered for the space station unless a significant advance in the performance of thermoelectric materials is achieved. The difficult solar concentrator problems eliminate solar thermionic conversion as a competitor in the 10- to 40-kw power level category. The nuclear thermionic system appears to be the ultimate space power concept promising low weight, long life, high reliability, and good growth potential. Demonstration of these characteristics, however, may not be possible until the middle 1970's. If the problems of the solar and nuclear dynamic systems are not completely resolved and their reliability demonstrated by the early 1970's, the nuclear thermionic system may be developed to the point that it will seriously compete with the older concepts.

VI. STUDY LIMITATIONS

A major obstacle to objective comparison of space power systems is the wide disparity in the development status of the candidate systems. Extensive flight test data are available for solar photovoltaic systems. Considerable laboratory testing has been performed on mercury Rankine and Stirling engines, but there is no performance data from complete system operation. Almost all closed Brayton cycle performance data available at this time are based solely on computer studies. Since all these data cannot be considered of equal validity when comparing systems, objective comparison is very difficult.

Another limitation results from the fact that differences in performance between similar devices can sometimes be verified only by extensive testing. The performance of the various types of concentrators is a typical example.

The limitations point to the necessity for periodically reviewing the results of the study to determine the effect of new data.

VII. IMPLICATIONS FOR RESEARCH

The study indicates that solar photovoltaic systems will probably be chosen for many spacecraft during the next ten years. Improvement of their performance requires advances in the state of the art of sealed cell batteries and solar cells. Batteries will undoubtedly also be used for many purposes in spacecraft with other types of power systems. Research aimed at the improvement of silver-cadmium cells can result in a notable advance in space power technology at moderate cost.

There does not appear to be a serious challenger to the conventional n/p silicon solar cell. A step increase in their performance is not likely, but research into materials and fabrication techniques can result in worthwhile improvements in efficiency, lower cost, and reduction in the size of the required arrays.

VIII. SUGGESTED ADDITIONAL EFFORT

Additional effort is suggested in two areas. One is regular updating of the final report of the study. The report is a comprehensive summary of the current status of space station power systems. By the expenditure of minimum effort, the report can be maintained current. There are several very important activities now in progress the results of which should be incorporated into the report. Typical of these are the nuclear power system studies being performed for NASA Lewis Research Center by the Martin and General Electric Companies. Also, AiResearch is planning to test a Brayton cycle system in the near future, and several flight tests of solar concentrators are planned. The first revision of the report may be planned for completion by September 1, 1964. Maintaining the report current will provide a continuous assessment of progress in space station power system development and allow more efficient planning of the space station program.

It is also suggested that a study be performed of space station electrical loads. The objectives of such a study are all aimed at reducing the size, cost, and complexity of the power system. The specific objectives are as follows:

- Determine the effect of variation in the quality of the electrical power on the utilization equipment and the power source.
- Determine methods of increasing the peak power output of the space station power system without significant effect on average power rating, cost, or mission accomplishment.
- Reduce total electrical load. When solar or nuclear energy sources are used, only 3 to 5 percent of the source power output becomes useful electrical power. An objective of the study would be to reduce total electrical load by the use of other forms of energy. For instance, heating loads may be supplied directly from the source, by catalytic reaction, or by radioisotope capsules.

Reduction of the power output requirements can significantly reduce the space station power system problem.